IJSPT

ORIGINAL RESEARCH

INFLUENCE OF ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION ON DYNAMIC POSTURAL CONTROL

Becky Heinert, MS, PT, SCS[1,3]
Kari Willett, SPT[2]
Thomas W. Kernozek, PhD, FACSM[2,3]

ABSTRACT

Background: Athletes that have had anterior cruciate ligament (ACL) reconstruction are at a greater risk for reinjury. The relationship between ACL reconstruction and the dynamic postural sway index (DPSI) has not yet been examined.

Hypothesis/Purpose: The purpose of this study was to examine the DPSI in a surgically reconstructed ACL limb compared to the uninjured leg in athletes that had been cleared for sport. It was hypothesized that in a bilateral limb comparison, the leg that underwent ACL reconstruction would demonstrate poorer postural stability measures (greater DPSI) during a single leg landing activity as compared to the non-surgical limb.

Design: Case-control study.

Methods: 14 subjects (7 male, 7 female; age range 16-23 years) with a history of unilateral ACL reconstruction and clearance for return to sport (mean 14 months post-operatively, range 8 to 24 months) performed five single leg hops over a 12 inch hurdle in the anterior direction from a distance corresponding with 40% of their height, onto a force platform. DPSI for the medial-lateral, anterior-posterior, vertical directions and a composite score were calculated for each trial on the surgical and non-surgical legs. A multivariate analysis with repeated measures was used to compare surgical and non-surgical legs for the total DPSI measure as well as for each component.

Results: Significant differences ($p < .05$) in dynamic postural stability were observed in the medial-lateral, anterior-posterior, vertical indices and DPSI total between the surgical and non-surgical limb.

Conclusion: Deficits in dynamic postural control persist in ACL-reconstructed limbs compared to the non-surgical limb after the clearance for full activity. Clinicians should consider assessing single limb dynamic stability prior to releasing the athlete back to full activity.

Level of evidence: Level 3

Keywords: Anterior cruciate ligament, Dynamic postural stability index, kinetics, single limb hop

[1] Gundersen Health System, La Crosse, WI, 54601, USA
[2] University of Wisconsin-La Crosse, Department of Health Professions, Physical Therapy Program, La Crosse, WI, 54601, USA
[3] La Crosse Institute for Movement Science, La Crosse, WI, 54601, USA

All authors report no conflict of interest based on this work.

CORRESPONDING AUTHOR
Thomas W. Kernozek, PhD, FACSM
University of Wisconsin-La Crosse
Department of Health Professions, Physical Therapy Program
1300 Badger Street, La Crosse, WI 54601, USA.
Work (608)785-8468, Fax (608)785-8460
E-mail: kernozek.thom@uwlax.edu

INTRODUCTION

Athletes that have sustained a tear to the anterior cruciate ligament (ACL) and return to sport after surgical reconstruction appear to be at a greater risk for ACL re-injury. The recurrence rate for a second ACL tear has been estimated to be between 6-25% within five years following reconstruction, with nearly 50% occurring in the contralateral limb, the majority as non-contact injuries.[1] Factors such as altered knee proprioception, decreased lower extremity strength, poor neuromuscular control, performance flaws in the biomechanics of landing, poor postural stability and fear avoidance beliefs have all been implicated in this greater risk of re-injury.[2–11]

In a clinical setting, postural stability is often determined statically as the athlete attempts to maintain their center of mass over a stationary base of support by comparing the amount of time that the individual can maintain their balance on their injured vs. non-injured limb.[12] This is used to assess lower extremity proprioceptive deficits. These measures are often incorporated in school and clinical settings because of the relative ease in which they can be administered and interpreted without sophisticated equipment. However, static postural stability measures alone have been described as insensitive, non-functional, and poorly related to dynamic values.[12–16] Alternatively, a measure that requires the individual to maintain their center of gravity over a base of support when moving or when an external perturbation is applied to the body may be a more challenging and sensitive method to assess changes in the limb's proprioceptive capabilities. Paterno et al.[3] reported deficits in dynamic postural stability that were predictive of a second ACL injury in surgically reconstructed participants using a Balance system with a moveable platform. However, since the majority of injuries to the ACL are non-contact and are often associated with more dynamic activities such landing, cutting or deceleration, it may be of greater value to assess postural stability during activities that are dynamic and more closely mimic the athletic activity.

Two methods are often used in measuring dynamic lower extremity postural control. The Dynamic Postural Sway Index (DPSI) measures limb stability using a single leg hop test onto a force plate. The DPSI is a highly reliable assessment (ICC = 0.96) and provides a composite score of anterior-posterior, medial-lateral, and vertical stability indices bases on the ground reaction forces.[17] This metric was developed with the underlying premise that dynamic postural stability largely depends on lower extremity kinematics, muscle activation and eccentric control utilized in landing.[17] Time to Stabilization (TTS) is another dynamic postural stability measure with good reliability that has been used to assess landing activities (ICC = .65-.79).[16] TTS is defined as the time required to minimize resultant ground reaction forces of a jump landing to within a range of the baseline, or static ground reaction force. TTS also provides information on directional forces occurring during landing (anterior-posterior, medial-lateral, and vertical), however the TTS methods utilize no composite score which may preclude observations regarding global changes in dynamic limb stability.[17] DPSI is considered a more reliable and precise measure of dynamic postural stability than TTS during a single leg hop activity.[17]

To date, no previous studies have evaluated postural stability in the ACL reconstructed population using DPSI methods. It is hypothesized that in a bilateral limb comparison, the leg that underwent ACL reconstruction would demonstrate poorer postural stability measures (greater DPSI) during a single leg landing activity as compared to the non-surgical limb.

METHODS

Subjects

All subjects or their parents provided their signed informed consent prior to participation approved by the university institutional review board. Fourteen subjects were recruited from the local area into the ACL reconstructed (ACLR) group each had received their surgical intervention within the prior two years and having received full clearance for athletic activity by their physician and physical therapist. All had some physical therapy intervention after surgery but all did not use the same surgeon nor therapist for treatment. Subjects were excluded from the study if they were experiencing any lower extremity or back pain.

Procedures

Upon arrival to the laboratory, anthropometric data were collected including height, weight, and activity level. All subjects were issued standardized footwear (625 New

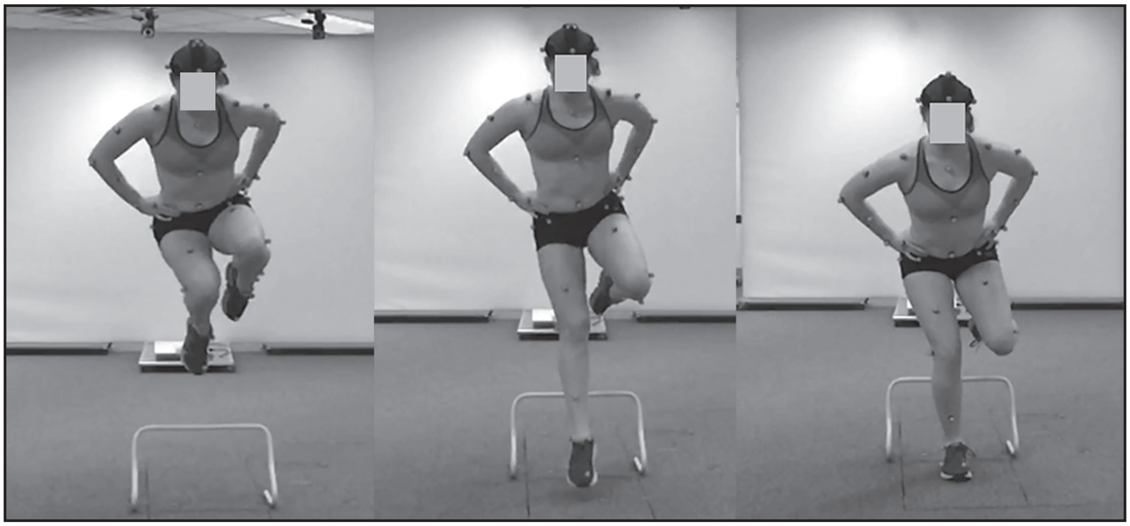

Figure 1. *Dynamic postural control index is calculated based on the performer hopping with both legs over a 12" barrier and landing on one leg with either their surgical or non-surgical limb.*

Balance, Boston, MA) and completed a five minute warm up on a stationary bicycle at a self-selected speed.

The subjects were asked to perform five successful single landings over a 12 inch hurdle in the anterior direction (Figure 1) onto a force platform sampled at 1200 Hz (Bertec Corp, Columbus, OH). The participants began from a distance corresponding with 40% of their height to the force platform. They were allowed to use their arms to propel themselves over the barrier and assist with obtaining postural control. Participants were given instructions to place their hands on their hips immediately following stabilization and hold that position for 10 seconds. If the subject flailed their arms during the terminal stabilization period, missed the force plate, made contact with the hurdle, touched the ground with the opposite leg or jumped with a single leg, the trial was repeated. Five trials were selected as this number has been shown to provide excellent reliability during similar single leg hop tasks for dynamic postural control indices (ICC = 0.90-0.97).[17] Prior to data collection, subjects were allowed as many practice sessions as needed in order to become familiar with the testing procedure. The order of the limb tested was randomized.

Analysis

Force data were filtered using a zero-lag fourth order low pass Butterworth filter with a 20 Hz cutoff frequency. Directional postural stability indices (ML, AP and vertical) and the composite dynamic postural stability index (DPSI) were calculated for the five trials for each leg (surgical and non-surgical). For each condition, mean postural stability indices of five trials were exported for statistical analysis. The first three seconds of the GRF data after impact, defined as the instant the vertical GRF exceeds 10N, was used to calculate a postural stability index in the ML, AP, and vertical (V) directions for each trial using the following root mean square equations presented by Wikstrom et al.[17]

$$\text{ML PSI} = \sqrt{\Sigma} \left\lceil (0\text{- GRFx})^2 / \text{number of data points} \right\rfloor$$

$$\text{AP PSI} = \sqrt{\Sigma} \left\lceil (0\text{- GRFy})^2 / \text{number of data points} \right\rfloor$$

$$\text{V PSI} = \sqrt{\Sigma} \left\lceil (\text{body weight- GRFz})^2 / \text{number of data points} \right\rfloor$$

where GRFx corresponds to the mediolateral GRF data, GRFy corresponds to the anteroposterior GRF data, and GRFz corresponds to the vertical GRF data.

A composite dynamic postural stability index (DPSI) was calculated using the following equation:

$$\text{DPSI} = \sqrt{} \left\lceil \Sigma(0\text{- GRFx})^2 + \Sigma(0\text{- GRFy})^2 + \Sigma(\text{body weight- GRFz})^2 / \text{number of data points} \right\rfloor.$$

A multivariate analysis with repeated measures was used to compare between the surgical and non-surgical leg for each DPSI component (ML PSI, AP PSI, V PSI) as well as the total DPSI with alpha set to 0.05. Follow up univariate tests (paired t-tests) were then performed separately on each DPSI component and total using the Bonferoni procedure.

RESULTS

Group demographics are reported in Table 1. Seven males and seven females participated in the study. The mean age of the subjects was 19 years (16-23), mean height of 171.1 ± 9.0 cm, mean weight of 76.5 ± 18.9 kg and mean Tegner score of 6 ± 2. Six participants had patellar tendon autografts, seven participants had hamstring autografts, and one participant had a hamstring allograft. The average time from surgery was approximately 14 months with a range of 8 to 24 months.

Multivariate analysis showed a difference between limbs (Wilk's lambda = .002, $p < 0.05$). Follow up univariate tests indicated that there were differences in all directional, dynamic postural stability indexes between the surgical and non-surgical limb for each direction as well as for the total score ($p < .05$) (Table 2). The indexes were higher on the surgical side by 24% in the medial-lateral direction, 9% in the anterior-posterior direction, 12% for vertical direction and 12% for the total DPSI.

DISCUSSION

Athletes that have had an ACL reconstruction appear to demonstrate differences in dynamic postural stability during a single limb jump-landing activity on their surgical limb when compared to their non-surgical limb within two years post-surgery. The participants in the current study demonstrated differences in DPSI total scores as well as all directional components.

The findings of the present study appear to be similar to Webster et al.[18] who reported deficits in TTS during a single leg maximum vertical hop and forward jump in Division I female athletes who had undergone ACL reconstruction compared to uninjured controls. In their analysis, the ACL reconstructed group took 0.11 seconds longer to stabilize after a jump landing as compared to the control group. These authors reported that their strong effect size suggested that this difference was clinically important and that athletes who have completed their rehabilitation and are cleared for sport may still lack the appropriate level of postural stability during a

Table 1. *Demographic data for 14 participants*

Subject	Gender	Height (cm)	Weight (kg)	Age (years)	Months since surgery	Graft type	Tegner score
1	F	171	62.27	16	12	Hamstring	8
2	F	168	55.45	23	12	Patellar Tendon	6
3	M	178.5	79.56	17	12	Patellar Tendon	1
4	M	183.5	100.9	26	12	Patellar Tendon	5
5	M	167	65.50	19	24	Hamstring	5
6	M	169	77.27	16	8	Hamstring	6
7	F	165	71.26	17	12	Hamstring	8
8	F	165	58.60	19	12	Hamstring	10
9	F	161.5	68.00	16	12	Patellar Tendon	7
10	F	163.5	58.60	20	18	Patellar Tendon	8
11	M	184.5	112.72	19	12	Patellar Tendon	10
12	M	182	106.20	22	24	Hamstring (allograft)	7
13	F	157	65.00	19	12	Hamstring	6
14	M	180	90	18	13	Hamstring	6

Gender: F=female, M=male. Graft type=hamstring is a hamstring autograft harvested from the patient, patellar tendon is a patellar tendon autograft harvested from the patient, Hamstring (allograft) is a hamstring graft harvested from a cadaver.

Table 2. *Means (± Standard Deviation) in Newtons for dynamic postural stability indices (Medial-lateral, Anterior-Posterior, Vertical and Total) in the non-surgical and surgical legs for Anterior Cruciate Ligament Reconstructed participants while landing during a single-leg hop test*

	Non-surgical Leg	Surgical Leg
Medial-Lateral (N)*	19.66 ± 4.81*	25.78 ± 5.72*
Anterior-Posterior (N)*	162.87 ± 12.49*	177.84 ± 11.93*
Vertical (N)*	401.79 ± 38.78*	457.45 ± 50.40*
Dynamic Postural Stability Index Total (N)*	435.72 ± 39.18*	494.90 ± 50.11*

*Indicates statistically significant differences ($p<0.05$)

task that mimics sport. The testing protocol in the current study was similar to Sell[12] who compared the standard deviation in force platform static variables of force with eyes open and closed to the DPSI in healthy athletes during a barrier jump. However, the mean total DPSI for the healthy subject's dominant leg in their investigation was 348 whereas in the current study the mean of the uninjured limb was 436 indicating poorer dynamic postural control overall.

Similarly, Mohammadi et al.[5] studied the relationship between static and dynamic postural stability in athletes an average of eight months after ACL reconstruction and reported differences in the surgical limb compared to the uninjured limb and compared to healthy controls for all parameters of postural stability including anterior-posterior and medial and lateral amplitude and velocity. Furthermore, the loading rates on the ACL reconstructed limb during a drop landing was approximately 45% greater than on the non-injured limb. These authors suggested that presence of residual postural stability asymmetries may predispose athletes to future re-injury. Differences in loading rates during dynamic tasks were also reported by Pratt and Sigward[19] in subjects 6-24 months after ACL reconstruction during single leg landing and running activities. The authors reported that the surgical limb peak power absorption was approximately 50% less than the uninjured limb and suggested that the ACL reconstructed subjects may be reluctant or unable to dynamically accommodate the forces at the knee. Although knee loading patterns were not specifically measured in the current study, subjects demonstrated greater vertical component of the DPSI which may indicate greater knee stiffness. It is plausible that the demands required during a single leg deceleration activity may be too great for the ACL reconstructed limb and could result in a landing pattern that is stiffer and require increased dynamic postural movements from other segments as the body attempts to stabilize the leg. To address this, clinicians should consider incorporating exercises that require adaptation to various loading variables such as during progressive plyometric training during the rehabilitation of the ACL reconstructed athlete. However, the relationship between knee loading variables and postural stability during dynamic activities requires further investigation.

Although time to stabilization has been used to provide information on dynamic postural stability and motor control in populations effected by ACL injury and functional ankle instability,[5,13,17,18] its relationship to DPSI in the ACL population is currently unknown. Intuitively, one would expect some relationship. However, in their comparison of dynamic control measures in injured runners, Meardon et al.[20] reported no differences in stability measures of the injured limb using the star excursion test or TTS during a single leg barrier jump but reported differences in the vertical postural stability index and DPSI composite scores. To date, there are no published studies that have utilized the DPSI to assess dynamic postural stability during single limb landing in the ACL reconstructed sample. Because the DPSI includes a global score as well as multiple directional force attenuation components (anterior-posterior, medial-lateral sway and vertical force), it may provide a comprehensive depiction of specific dynamic postural sway deficits that the athlete utilized to absorb ground reaction forces in landing. This may serve to better guide decisions regarding an athlete's readiness for return to play. It appears that that these ACL reconstructed participants had a poorer total DPSI as well poorer outcomes during each component. However, the cause and relevance of the directional component differences are currently unknown and may be influenced by individual differences in lower extremity strength, calf flexibility, innate foot architecture and previous injury history including chronic ankle instability which has previously been related to decreased dynamic balance using TTS and DPSI measures.[14,21]

Changes in knee proprioception after ACL injury and post reconstruction have been widely reported within the literature.[3,5,18,22,23] The ACL mechanoreceptors are thought to provide direct afferent information to the spinal cord and supraspinal area regarding joint position, knee motion, and tissue deformation.[5] Schutte et al.[22] reported the neurologic composition of the ACL include neural connections from the ACL to the spinal cord and supraspinal areas. Following reconstruction of the ligament, restoration of the sensory function may not fully recover. Young et al.[24] found no evidence of mechanoreceptor reinnervation in reconstructed ACLs an average of 6.9 years after surgery. This lack of sensory input may influence dynamic postural stability and movement strategies in the ACL reconstructed athlete.

The most commonly described methods of measuring knee proprioception are joint position sense and threshold to detect movement.[25–27] Despite the general agreement regarding the loss of the proprioceptive mechanoreceptors from the native ACL after ACL reconstruction, the validity of the current testing strategies to measure this change continues to be debated.[23,27,28] Relph and Herrington[23,29] reported differences in knee joint position sense as measured in the ability to actively reproduce knee joint position after passive positioning in two separate investigations while Littmann et al.[26] reported no difference after ACL reconstruction. In a meta-analysis of proprioception acuity measures following ACL injury, Gokeler et al.[27] concluded that there is limited evidence that proprioceptive deficits as detected by the commonly used tests adversely affect function in subjects returning to sports. Likewise, Relph and Herrington[23] reported that the minor differences in knee proprioceptive sense may not influence performance or the likelihood of a second injury. Therefore, the application of the DPSI to the ACL population may provide a more clinically relevant assessment tool that could provide a link between biomechanical and neurosensory characteristics in a more dynamic and challenging environment.

The relationship between ACL re-injury and some aspects of postural stability have been previously examined. Paterno et al.[3], reported that individuals with residual balance deficits in their surgical knee as compared to the non-surgical limb were twice as likely to sustain a second injury to the ACL as compared to those without postural differences. Their study used a Biodex Balance System to evaluate unilateral postural stability while standing on a force plate. Although this system uses a moveable force platform, it still may be considered a more static examination of postural sway with debatable application or relationship to a more dynamic, sport-specific task. Previous authors have also reported a poor relationship between static and dynamic postural stability measures.[12,16,21] Sell[12] reported very poor correlations ($r = .05$-$.23$) between static and dynamic measures of postural stability in healthy adults using a single leg balance test with eyes open and eyes closed compared to the DPSI measures from a forward and lateral hop. In their study of athletes with functional ankle instability, Ross et al.[16] reported poor to moderate reliability for anterior-posterior (ICC = .32) and medial-lateral sway (ICC = .60) during single leg standing while TTS following a single leg vertical jump in the same subjects displayed either poor to moderate reliability (ICC = .61) for anterior-posterior and .80 for medial-lateral force components. Together, these findings may suggest that assessing dynamic postural stability during a dynamic task may be a more sensitive means of determining balance deficits. However, the relationship between the dynamic postural control indices and ACL re-injury certainly warrants further investigation.

Participants in the present investigation displayed greater vertical postural instability in the surgical limb suggesting that the ACL reconstructed extremity was not able to attenuate the vertical ground reaction force as well compared to the non-surgical side. In addition to the sensorimotor adaptations that presumably occur following ACL reconstruction, changes in the ability to absorb the vertical ground reaction forces may be related to alterations in lower extremity joint moments and muscle activation patterns that were not examined in the current study. Numerous studies have reported changes in landing patterns after ACL reconstruction.[3,30–34] Lower extremity asymmetries between limbs including decreases in knee extension moments, changes in peak vertical ground reaction forces and loading rates have been well-documented in the ACL reconstructed patient.[30–33] Furthermore, these differences appear to persist for even 2-3.5 years post ACL reconstruction.[5,33] Although the relationship between deficits in dynamic postural control and lower extremity force production was not directly studied in the present investigation, it is plausible that lower extremity compensatory mechanisms may be required to achieve single limb stability due to interruption of the normal sensorimotor planning required for high level coordinated movements. Nyland et al.[35] suggested that altered afferent feedback may result in the motor cortex propagating a modified motor plan that is more reliant on proximal and distal segments such as the hip or ankle complex. Compensatory movement patterns such as excessive truncal movements, hip internal rotation, increased knee valgus and decreased knee flexion angles may be present during landing as the proximal stabilizers are required greater role in dynamic stability.[3,30,36,37] Altered sensorimotor programming may also influence the ability of the surgical limb to generate force and power production that are necessary during athletic activities. A stiffer landing pattern due to deficits in quadriceps or hamstring recruitment or greater reliance of the gastrocnemius during jumping may be observed in athletes as they transition to sports-related activities.[3,30,33,37–40] Dai et al.[31] also reported decreases in knee joint moments in ACL reconstructed subjects, suggesting that these changes may be attributed to deficits in dynamic strength, muscle inhibition, altered neuromuscular function or fear avoidance beliefs. These factors may influence an athlete's ability to return to a previous level of sport and play a role in the incidence of a second ACL.

Myer et al.[9] compared the effects of plyometric versus dynamic stabilization balance training on power, balance, and landing force in healthy female athletes. They reported that both types of training programs are effective at increasing measures of neuromuscular power by improvements in vertical jump performance (approximately 4 centimeters in the balance group and 2.5 centimeters in the plyometric group), and an average increase of 11.6% greater torque of the knee flexors measured isokinetically. However, differences were shown in lower extremity force attenuation in the dominant leg with the balance group having a 7% decrease in impact force whereas the plyometric group had a 7.6% increase. Both training groups demonstrated a decrease in medial-lateral single leg sway after landing from a single leg hop with their dominant leg. These authors suggested that the absence of balance and dynamic control activities where subjects are required to control their landing may have had influence on force dissipation during single limb landing.[9] In the present study, the relationship between DPSI and the surgical limb's ability to generate the power performance measures important to sports performance was not examined. The persistence of limb differences in dynamic postural stability may predispose ACL reconstructed athletes to re-injury and should likely need to be considered when determining readiness for a full return to sport. Furthermore, the relationship between the DPSI and athletic performance factors important for the return to play appears to warrant future investigation.

CONCLUSION

The results of the present investigation indicate that deficits in dynamic postural control as measured during a single limb landing persist in ACL-reconstructed limbs compared to the non-surgical limb after the clearance for full activity. These deficits may lead to abnormal landing patterns that may place the athlete at risk for re-injury. These findings appear to support the assessment of dynamic postural control measures prior to the return to sport.

REFERENCES

1. Schilaty ND, Nagelli C, Bates NA, et al. Incidence of second anterior cruciate ligament tears and identification of associated risk factors from 2001 to 2010 using a geographic database. *Orthop J Sports Med*. 2017;5(8):2325967117724196. doi:10.1177/2.
2. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther*. 2006;36(6):385-402.
3. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968-1978.
4. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Hewett TE. Effects of sex on compensatory landing strategies upon return to sport after anterior

cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2011;41(8):553-559.

5. Mohammadi F, Salavati M, Akhbari B, Mazaheri M, Khorrami M, Negahban H. Static and dynamic postural control in competitive athletes after anterior cruciate ligament reconstruction and controls. *Knee Surg Sports Traumatol Arthrosc*. 2012;20(8):1603-1610.
6. Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. *J Orthop Sports Phys Ther*. 1994;20(2):60-73.
7. Wojtys EM, Huston LJ. Longitudinal effects of anterior cruciate ligament injury and patellar tendon autograft reconstruction on neuromuscular performance. *Am J Sports Med*. 2000;28(3):336-344.
8. Wild CY, Steele JR, Munro BJ. Insufficient hamstring strength compromises landing technique in adolescent girls. *Med Sci Sports Exerc*. 2013;45(3):497-505.
9. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. *J Strength Cond Res*. 2006;20(2):345-353.
10. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2012;42(9):750-759.
11. Chmielewski TL, Jones D, Day T, Tillman SM, Lentz TA, George SZ. The association of pain and fear of movement/reinjury with function during anterior cruciate ligament reconstruction rehabilitation. *J Orthop Sports Phys Ther*. 2008;38(12):746-753.
12. Sell TC. An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults. *Phys Ther Sport* . 2012;13(2):80-86.
13. Colby SM, Hintermeister RA, Torry MR, Steadman JR. Lower limb stability with ACL impairment. *J Orthop Sports Phys Ther*. 1999;29(8):444-451; discussion 452-454.
14. Brown CN, Mynark R. Balance deficits in recreational athletes with chronic ankle instability. *J Athl Train*. 2007;42(3):367-373.
15. Harrison EL, Duenkel N, Dunlop R, Russell G. Evaluation of single-leg standing following anterior cruciate ligament surgery and rehabilitation. *Phys Ther*. 1994;74(3):245-252.
16. Ross SE, Guskiewicz KM. Examination of static and dynamic postural stability in individuals with functionally stable and unstable ankles. *Clin J Sport Med* . 2004;14(6):332-338.
17. Wikstrom EA, Tillman MD, Smith AN, Borsa PA. A new force-plate technology measure of dynamic postural stability: the dynamic postural stability index. *J Athl Train*. 2005;40(4):305-309.
18. Webster KA, Gribble PA. Time to stabilization of anterior cruciate ligament-reconstructed versus healthy knees in national collegiate athletic association division I female athletes. *J Athl Train*. 2010;45(6):580-585.
19. Pratt KA, Sigward SM. Knee loading deficits during dynamic tasks in individuals following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther*. 2017;47(6):411-419. .
20. Meardon S, Klusendorf A, Kernozek T. Influence of injury on dynamic postural control in runners. *Int J Sports Phys Ther*. 2016;11(3):366-377.
21. Ross SE, Guskiewicz KM, Gross MT, Yu B. Balance measures for discriminating between functionally unstable and stable ankles. *Med Sci Sports Exerc*. 2009;41(2):399-407.
22. Schutte MJ, Dabezies EJ, Zimny ML, Happel LT. Neural anatomy of the human anterior cruciate ligament. *J Bone Joint Surg Am*. 1987;69(2):243-247.
23. Relph N, Herrington L. Knee joint position sense ability in elite athletes who have returned to international level play following ACL reconstruction: A cross-sectional study. *The Knee*. 2016;23(6):1029-1034.
24. Young SW, Valladares RD, Loi F, Dragoo JL. Mechanoreceptor reinnervation of autografts versus allografts after anterior cruciate ligament reconstruction. *Orthop J Sports Med*. 2016;4(10):2325967116668782.
25. Relph N, Herrington L, Tyson S. The effects of ACL injury on knee proprioception: a meta-analysis. *Physiotherapy*. 2014;100(3):187-195.
26. Littmann AE, Iguchi M, Madhavan S, Kolarik JL, Shields RK. Dynamic-position-sense impairment's independence of perceived knee function in women with ACL reconstruction. *J Sport Rehabil*. 2012;21(1):44-53.
27. Gokeler A, Benjaminse A, Hewett TE, et al. Proprioceptive deficits after ACL injury: are they clinically relevant? *Br J Sports Med*. 2012;46(3):180-192.
28. Howells BE, Ardern CL, Webster KE. Is postural control restored following anterior cruciate ligament reconstruction? A systematic review. *Knee Surg Sports Traumatol Arthrosc* . 2011;19(7):1168-1177.
29. Relph N, Herrington L. The effect of conservatively treated ACL injury on knee joint position sense. *Int J Sports Phys Ther*. 2016;11(4):536-543.

30. Orishimo KF, Kremenic IJ, Mullaney MJ, McHugh MP, Nicholas SJ. Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(11):1587-1593.
31. Dai B, Butler RJ, Garrett WE, Queen RM. Using ground reaction force to predict knee kinetic asymmetry following anterior cruciate ligament reconstruction. *Scand J Med Sci Sports*. 2014;24(6):974-981.
32. Decker MJ, Torry MR, Noonan TJ, Riviere A, Sterett WI. Landing adaptations after ACL reconstruction. *Med Sci Sports Exerc*. 2002;34(9):1408-1413.
33. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med* . 2007;17(4):258-262.
34. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower extremity compensations following anterior cruciate ligament reconstruction. *Phys Ther*. 2000;80(3):251-260.
35. Nyland J, Gamble C, Franklin T, Caborn DNM. Permanent knee sensorimotor system changes following ACL injury and surgery. *Knee Surg Sports Traumatol Arthrosc* . 2017;25(5):1461-1474.
36. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492-501.
37. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *J Orthop Sports Phys Ther*. 2013;43(11):777-792,
38. Decker MJ, Torry MR, Noonan TJ, Riviere A, Sterett WI. Landing adaptations after ACL reconstruction. *Med Sci Sports Exerc*. 2002;34(9):1408-1413.
39. Miranda DL, Fadale PD, Hulstyn MJ, Shalvoy RM, Machan JT, Fleming BC. Knee biomechanics during a jump-cut maneuver: effects of sex and ACL surgery. *Med Sci Sports Exerc*. 2013;45(5):942-951.
40. Morgan KD, Donnelly CJ, Reinbolt JA. Elevated gastrocnemius forces compensate for decreased hamstrings forces during the weight-acceptance phase of single-leg jump landing: implications for anterior cruciate ligament injury risk. *J Biomech*. 2014;47(13):3295-3302.